

AUGMENTED REALITY TECHNOLOGY

This is a continuation of U.S. Patent Application S.N. 09/286,817, filed April 6, 1999, which in turn claims the benefit under 35 U.S.C. §119(e) of provisional application Serial No. 60/081,051, filed April 8, 1998. The disclosures of both of those documents are hereby incorporated by reference as if set forth fully herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention.

The present invention relates, generally, to tracking apparatus and methods and to augmented reality (AR) technology for integrating or augmenting real information such as actual or captured real-world images with virtual information such as images of computer-generated objects. More particularly, the invention relates to a fiducial-based tracker or to a fiducial-based means for registering the virtual-world information to the real-world information within an AR system.

2. Description of the Related Technology

AR technology allows a person to see or otherwise sense a computer-generated virtual world integrated with the real world. The "real world" is the environment that an observer can see, feel, hear, taste, or smell using the observer's own senses. The "virtual world" is defined as a generated environment stored in a storage medium or calculated using a processor. A tracker system within the AR technology registers the virtual world to the real world to integrate virtual and real information in a manner usable by the observer.

AR technology essentially "connects" a human user to a database or to a virtual or partially virtual environment using any combination of the human user's visual or aural or kinesthetic senses. Alternatively, AR technology can be viewed as connecting the partially virtual environment to the real environment as observed by the human user. AR technology allows the human user to perceive and be guided by processed database information that is integrated with the real world. Additionally, AR technology may enable a human to participate

5 in an activity in a virtual world by translating the human user's movements or activity within a defined area or volume of the real world into the desired response in the virtual world.

Visual AR technology includes "Video See Through" AR technology and "Optical See Through" AR technology. Video See Through AR technology uses a camera to capture real world images and electronically adds or integrates the virtual images to create the augmented
10 image. Optical See Through AR technology projects the virtual images on a see-through display, enabling a human user to see the projected image of the virtual object on the display and the images of the real world objects through the display.

By allowing a human to quickly, accurately and appropriately retrieve and apply virtual information to a problem, a task or situation in the real world, AR technology provides
15 significant benefits in a society that is being inundated with information. For example, because of the quick development of many new technologies, the time required to train a person or to assemble and service complex products is increasing. New products are being quickly introduced into the market while many older generations of products are being concurrently used by the general public. An AR system can augment or enhance the real world view of the
20 equipment with instructional text, drawings and diagrams to enable service professionals to quickly, accurately, and competently work on the equipment. There are many other examples of the benefits provided by the AR technology, including but not limited to the following examples. The invention can be used to improve the efficiency and quality of assembling or inspecting components such as televisions, radios, computers, and other components. Similarly, the
25 invention can be used to improve the efficiency and quality of servicing or maintaining systems by superimposing text, pictures, drawings, schematics, and other information from maintenance manuals, for example, upon a real-world object. An AR system can be used to simulate real world activities, such as piloting aircraft or ships, and further can be used for instructional training, education, or rehearsals. Additionally, the invention can be used to create games or
30 other entertainment, or to form an artistic medium by capturing and manipulating the artist's motions. Furthermore, the invention can be used to document head and eye responses to stimuli by tracking and recording the motion of either the user's head or the user's pupil after a stimuli has been introduced.

5 The AR system of the present invention has been used to fabricate wire harnesses for commercial airline planes. Each commercial airliner typically contains hundreds of wire bundles and hundreds of miles of wire. As shown in Figure 3, the known art requires an assembly worker to bundle the wires around pegs formed on plywood boards by viewing printouts of wiring diagrams and transposing the information to the board. The known method for
10 fabricating wire harnesses is a slow and tedious process that can result in expensive and time-consuming mistakes, and contributes to the billions of dollars that the airline industry loses because of production delays. The boards are specially designed for various wire harnesses, and must be stored. However, the wire harness fabrication AR system and embodiment of the present invention has been shown to reduce cycle time by fabricating the quality wire harnesses
15 up to 50% faster than the current methods, and enables planes, particularly the wire harnesses, to be quickly designed and produced according to the special requirements of a customer.

 An AR system should allow a human user to easily and naturally interact with objects in both the real and virtual world. Therefore, a visual AR system should: (1) quickly and accurately detect and track input data such as coordinate marks or fiducials; (2) quickly process the input
20 data to determine the relative position and orientation between the user and the target objects and register the virtual world objects to the real world objects; and (3) quickly and smoothly integrate the virtual world objects with the real world objects either by displaying or projecting an image of the virtual world objects over the real world objects or by electronically combining an image of the virtual world objects with a captured image of the real world objects. Therefore, an AR
25 system should have a small latency period and a quick update rate. "Latency" is defined as the period of time between the moment when the input data is captured and the moment that the augmented information is displayed or otherwise presented in usable form to the user. "Update rate" is defined as the frequency of refreshing the displayed or otherwise presented information that is processed from new input data. Humans perceive their environment with an essentially
30 continuous update rate and zero latency period. Therefore, a human will be able to easily and naturally interact with an AR system that has an update rate and latency period approaching a human's natural capabilities; *i.e.*, "real time" or "near real time." An update rate of at least 60 Hertz and a latency period of 16 milliseconds or less is considered "near real time."

5 Known trackers include magnetic-based, moving infrared beam optical-based, light source (LED) optical-based, ultrasonic-based, and mechanical-based trackers. Problems associated with these trackers generally include stray fields, noise, cost, insufficient accuracy, and limited mobility. Magnetic or moving infrared beam optical based trackers have been used in fighter aircraft and helicopters. These trackers accurately measure the user's pose with update
10 rates of twenty Hertz or greater, but are complex systems that work within a very limited volume and severely limit the mobility of a user. Furthermore, magnetic-based trackers are sensitive to and their accuracy may be detrimentally affected by metallic objects in the vicinity of the sensors. Light source-based trackers use a camera to track various light source patterns, such as Light Emitting Diode (LED) arrays, that are placed on a surface of a target object. These light
15 source-based trackers are effective in limited volumes and severely restrict the movement of the user. Additionally, these trackers have a limited accuracy and a latency greater than 100 milliseconds. Ultrasonic-based trackers are subject to noise interference in practical environments. The light source-based and ultrasonic-based trackers use "beacons" or "active" fiducials. An active fiducial generates a signal that is detectable by a sensor. Mechanical
20 tracking systems, comprising a pantograph arm attached to a head mounted display, have been used in U.S. Army gunship helicopters. These mechanical-based trackers also severely restrict the mobility of the user.

Applicants' invention provides an AR system, including a fiducial-based tracker system, which is believed to constitute an improvement over existing technology.

SUMMARY OF THE INVENTION

25 The present invention provides an apparatus and method for tracking the position and orientation between at least one sensor and at least one object, wherein either, or both, the sensor and the object may be mobile. The tracker system of the present invention is used as a means for
30 registering the virtual information to real world information within an augmented reality (AR) system. Proper registration in an AR system enables a user to correctly view a virtual scene and be guided to properly place or otherwise interact with real objects in an augmented view. The registration process conducted by the tracker system calculates six tracking parameters that determines the relative position and orientation between at least one real world object or target

5 and at least one sensor. The tracking parameters including three orientation parameters (the angles ϕ , θ and ψ) and three position parameters (distance $[L]$ and the intercept of the user's line of sight with the fiducial plane $[X\text{-bar}$ and $Y\text{-bar}]$). The tracker system continuously calculates or tracks these parameters because the target(s) and / or the sensor(s) are mobile.

10 An AR system operates with a volume formed by boundaries defined by the position of the sensor(s) and the tracked, real world object(s). The tracking system may be designed as either a 2-dimensional or 3-dimensional tracker. Additionally, the tracking system may use monocular or binocular optics to display data. The 2-dimensional tracker tracks the position of objects on an object plane, such as a wiring board. The 3-dimensional tracker tracks the position of objects on or in an object volume. The monocular AR system projects an image into one eye.

15 The binocular tracker projects slightly modified augmented images to both eyes to enhance the augmented view with depth perception. A monocular AR system incorporating the 2-dimensional tracker may be used to fabricate a wire harness for a vehicle, aircraft, or other object. Fiducials are placed on or near the board on which the wire harness is assembled. The augmented reality technology allows a human to simultaneously view a virtual image identifying

20 the correct wire path. Additionally, a monocular AR system incorporating the 2-dimensional tracker may be used to enhance the reading and interpretation of maps and charts. Virtual legends and text may be superimposed on a map or a virtual map may be superimposed over the real world objects. For example, a field soldier may view virtual images or information about troop movements generated by current military intelligence while viewing a real world map, and

25 then switch perspective and begin looking around at the real world field with a virtual map properly oriented and superimposed over his current field of vision. Other examples of enhanced processes include inspection of parts and electrical panel wiring. A monocular AR system incorporating the 3-dimensional tracker may be used to wire fuselages. A binocular AR system incorporating either a 2-dimensional or 3-dimensional tracker may be used to enhance medical

30 processes and devices, such as endoscopes and surgical devices.

The tracker system generally comprises a sensor or sensors for detecting a pattern of fiducials disposed on an object surface and processor connected to the fiducials on the other surface, which is identified by the processor by acquiring or matching a detected pattern of fiducials with a reference pattern of fiducials. The reference pattern of fiducials may be stored in

5 a computer memory as a data file. In a preferred embodiment, the pattern of fiducials includes a geometrically consistent hard fiducial pattern and a pseudo random soft fiducial pattern. The hard fiducial pattern is used to identify the phi, theta, and psi orientation parameters to the L position parameter. The soft fiducial pattern is used to identify the X-bar and Y-bar position parameters.

10 The AR system generally comprises a pattern of fiducials disposed on an object surface, a computer having a processor and a memory, an interface for receiving input and presenting AR output to a user, and a tracker system for detecting the pattern of fiducials and determining the relative position between the user and the target object. The tracker includes at least one sensor for detecting the pattern of fiducials. The sensor is electrically connected to the computer, and
15 has a position and an orientation with respect to the pattern of fiducials on the object surface. The processor identifies the position and the orientation of the sensor with respect to said object surface by matching a detected pattern of fiducials with a reference pattern of fiducials stored in the memory of the computer. In a preferred embodiment, the pattern of fiducials includes a geometrically consistent hard fiducial pattern and a pseudo random soft fiducial pattern, the
20 computer is a wearable computer, the interface has an update rate of at least 60 Hertz and a latency below 16 milliseconds, and the sensor is an optical sensor or camera capable of detecting passive fiducials.

The method for tracking the position and orientation of an object generally comprises the steps of scanning across an object to detect fiducials and form video "runs," clumping video runs
25 to detect a pattern of fiducials, acquiring estimated values for a set of tracking parameters by comparing a detected pattern of fiducials to a reference pattern of fiducials, and iterating the estimated values for the set of tracking parameters until the detected pattern of fiducials match the reference pattern of fiducials to within a desired convergence. In a preferred embodiment, the step of clumping video runs includes the steps of combining adjacent video runs and only
30 recording pixels having a video level above a predetermined threshold. The step of acquiring estimated values for a set of tracking parameters includes the steps of corresponding a predetermined number of detected hard fiducials with a reference pattern of fiducials to estimate the orientation parameters and the distance position parameter, and electing at least one of the

5 soft fiducials with the reference pattern of fiducials to estimate the X-bar and Y-bar position parameters.

The method for augmenting reality generally comprises the steps of disposing a pattern of fiducials on an object surface, tracking the position and orientation of the object, retrieving and processing virtual information stored in a computer memory according to the position and orientation of the object, and presenting the virtual information and the real information to a user
10 in near real time. In a preferred embodiment, the pattern of fiducials include a geometrically consistent hard fiducial pattern and a pseudo random soft fiducial pattern; and the steps of tracking the position and orientation of the objection, retrieving virtual information, and presenting the virtual information with real information are performed with an update rate of at
15 least 60 Hertz and a latency below 16 milliseconds.

The features, benefits and objects of this invention will become clear to those skilled in the art by reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure 1 is a schematic design illustrating the tracker and the AR system of the present invention.

Figure 2 is a schematic block diagram of the Video Feature Extractor (VFE) of the present invention.

Figure 3 illustrates a prior art method of fabricating a wire harness.

25 Figure 4 illustrates a wire harness fabrication AR system embodiment of the present invention.

Figure 5 illustrates a WireCAD screen display used to create virtual images of wire harness schematics in an embodiment of Figure 4.

Figure 6 illustrates the augmented view of a virtual image of a wire path superimposed
30 over a real world image of the wiring board and a real wire.

Figure 7 illustrates a menu driven interface used in the AR system.

Figure 8 illustrates the menu driven interface of Figure 6 with a cursor placed over the MENU selection which is thereby activated for selection.

5 Figure 9 is an illustration of an excerpt of a wiring board used in a wire harness fabrication AR system on which a wire harness is being assembled.

 Figure 10 is another view of the illustration of Figure 9.

 Figure 11 is an illustration of a wiring board used in a wire harness fabrication AR system.

10 Figure 12 is an illustration of an excerpt of a wiring board used in a wire harness fabrication AR system, showing the assembly of another wire harness.

 Figure 13 is an illustration of the fiducial pattern on a wiring board.

 Figure 14 is an illustration of a wiring board for use in wire harness fabrication AR system in which the fiducial pattern area and the wire harness assembly area are in separate

15 regions.

 Figure 15 is a side view of a head mounted display of the present invention.

 Figure 16 is a front perspective view of the head mount display of Figure 15.

 Figure 17 is a front view of the head mounted display of Figure 15.

 Figure 18 is a rear perspective view of the head mounted display of Figure 15.

20 Figure 19 illustrates the geometry represented by the six tracking parameters, including the orientation parameters (ϕ , θ and ψ) and the position parameters (L , \bar{X} and \bar{Y}).

 Figure 20 illustrates the relationship between the hard fiducials and the floating or soft fiducials.

 Figure 21 illustrates a possible image of a pattern of fiducials captured by the head
25 mounted display camera for a given set of orientation and position tracking parameters.

 Figure 22 illustrates the correspondence between four detected hard fiducials and four virtual fiducials predicted from previous tracking parameters.

 Figure 23 is a flow chart of a method for tracking the position and orientation of an object of the present invention.

30 Figure 24 is a flow chart of the acquire routine for the Correspondence and Election processes shown in Figure 23.

5 **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

 The present invention provides a tracker system and an augmented reality (AR) system. Referring to Figure 1, an example of a preferred embodiment of the AR system that incorporates embodiment of the tracker system is illustrated and generally indicated by the reference numeral 10. The AR system 10 is described below first in terms of its major structural elements and then
10 in terms of its secondary structural and/or functional elements which cooperate to track the position and orientation of an object, retrieve and process virtual information according to the position and orientation of the object, augment the real information with the virtual information, and present the augmented information.

 The tracker system, or tracker, identifies the relative position and orientation between at
15 least one sensor and at least one target object. Either, or both, the sensor(s) and the object(s) may be mobile. The tracker system provides a means for registering virtual information to real world information within the AR system, which enables a user to correctly view a virtual scene and be guided to properly place or otherwise interact with real objects in the augmented view. The registration process performed by the tracker calculates six tracking parameters that
20 determines the relative position and orientation between real world object(s) or target(s) and the sensor(s), and continues to calculate these parameters to determine the relative position(s) of the mobile target(s) and / or the sensor(s). An AR system operates within a volume formed by boundaries defined by the position of the sensor(s) and the tracked, real world object(s). The tracker may be used to track the position and orientation of a person's head, field of view, or any
25 mobile or moveable object or being with the volume. The AR system uses the position and orientation information provided by the tracker to display, for example, the correct location to place an object, the appropriate view in a virtual scene, or visual instructions to guide a user to achieve a desired hand-eye coordinated result.

 The figures illustrate an embodiment of a visual AR system, particularly a wire harness
30 fabrication AR embodiment. Other uses of the AR system are anticipated for various applications and are believed to fall within the teaching of the tracker system and the AR system described herein. Although the figures the following specification are directed toward a visual AR system, the AR system may be adapted to augment information directed toward any single or

5 any combination of a human user's means for sensing the environment, including the visual, aural, and kinesthetic senses.

Referring again to Figure 1, the AR system 10 generally comprises a pattern of fiducials 12 disposed on an object surface 14, a computer 16 having both a processor 18 and a memory 20, an interface 22 for receiving input and presenting augmented reality output to a user 24, and a
10 tracker for detecting the pattern of fiducials 12 and identifying the relative position and orientation between an object or object surface 14 and the user 24, for example. The tracker generally includes at least one sensor 26 for detecting the pattern of fiducials 12 and the processor 18 of the computer 16. The sensor 26 is electrically connected to the computer 16, has a position and an orientation with respect to the pattern of fiducials 12 on the object surface 14,
15 and generates a signal that corresponds to the pattern of fiducials 12 on the object surface 14, and generates a signal that corresponds to the pattern of fiducials 12 as detected by the sensor 26. The tracker calculates the tracking parameters that determine the position and the orientation of the sensor 26 with respect to the object surface 14 by matching the detected pattern of fiducials with a reference pattern of fiducials stored in the memory 20 of the computer 16. In the wire
20 harness fabrication AR system, the object surface 14 may comprise the wiring board shown in Figures 4, 6, and 9-14. However, any 2-dimensional or 3-dimensional form, shape or volume may function as the object surface 14.

Referring to Figures 1, 4 and 15-18, the computer 16 is preferably a wearable computer that provides mobility to a user 24 of the AR system 10. A user interface, including a display 36
25 and an actuation or selection device, is attached to the computer 16. The figures illustrate an embodiment where the sensor 26 and the display 36 are attached to a headset 38. The computer 16 accounts and compensates for the offset between the sensor 26 and the display 36 on the headset 38 to properly register or align the virtual image to the real image and form an augmented view for the user 24. By calculating and applying the appropriate offset, the tracker
30 can identify the position of the user 24, the user's eye, or other objects or beings. This offset may be accurately determined for a particular user by having the user 24 align a virtual T-mark with a real T-mark 62 in a start-up routine. It is noted that the pupils of the user's eyes may themselves form a fiducial that is tracked by a sensor having a known position and orientation, allowing the direction of the user's eyes or the user's field of vision to be determined. Therefore,

5 the user 24 may provide input to the AR system 10 merely by changing his or her direction of gaze.

The head-mounted display 36 may comprise either a Video See Through display or an Optical See Through display. With regard to the Video See Through display, the processor 18 in the computer 16 combines virtual object information 42 with real object information 44, which
10 may have been captured by a camera for example, and then projects or otherwise presents the augmented information or view 62 to the user 24. With regard to the Optical See Through display, the processor 18 in the computer 16 projects or otherwise presents the virtual object information 42 onto the display 36 and the user 24 views real object information 44 through the display 36. Figure 6 illustrates the augmented view 46 presented by the Optical See Through
15 display 36, which is incorporated into the design shown in the figures. The headset 38 preferably is adjustable, weighs less than 1 ½ pounds, and has an evenly distributed or balanced weight allowing a user 24, such as an assembly worker, to comfortably wear the headset 38 for long periods of time. Additionally, the headset 38 design shown in the figures will not interfere with contacts or eyeglasses worn by a user 24.

20 As shown in Figures 1 and 15-18, signal processing and power electronics 46 are also attached to the headset 38. These electronics 46 provide electrical power to all of the electrical components in the headset 38, process the input signals corresponding to a detected pattern of fiducials generated by the optical sensor or camera 26, transmit the input signals to the computer 16, and process the output video signals generated by the computer 16 to the head-mounted
25 display 36 where the augmented information is presented to the user 24.

Various software 52 operates within the computer 16, including an operating system 54 to control memory management, scheduling, input and output, an other activities of the computer 16, a tracker application software program 56 used to continuously calculate the tracking parameters that determine the position and orientation of the sensor and the objects, a display
30 graphics software program 58 used to form and/or present the augmented information to the user 24, and system data files 60 containing, among other information, data identifying a reference pattern of fiducials corresponding to the pattern of fiducials 12 on the object surface 14 and data related to the virtual information that is integrated with real information. In the embodiment shown in the figures, the tracker application software program 56 performs routines to determine

5 and track the position and orientation of the head mounted sensor with respect to the object surface(s) 14 where the pattern of fiducials 12 are located. The tracker application software program 56 is preferably a terminate-stay-resident program that continuously operates in the memory 20 of the computer 16 in order to continuously track the target object(s) 14 and other objects or beings. The processor 18 uses system data files to account and compensate for the
10 offset between the sensor 26 and the display 36 on the headset 38 to determine the field of view for the user 24. The display graphics software 58 retrieves or otherwise generates the appropriately registered virtual image to be integrated with the real images in the current field of the user 24, and presents the augmented image to the user 24 using the display 36. The virtual image may be converted or extracted from a CAD drawing, such as a WireCAD design drawing
15 for the wire harness fabrication AR system. Figure 5 illustrates a WireCAD screen display of a wire representation for a wire harness design.

As shown in the augmented view 62 of Figure 6 that is presented on an Optical See Through display 36, the tracker accurately registers the field of view of the user 24 with respect to the real object 14 (a wiring board). The virtual image 42 (a WireCAD generated wire
20 representation) overlays the object plane where the real object 44 (wire) should be placed. The wiring harness fabrication AR system embodiment has been shown to function in a volume of 4 feet x 60 feet x 4 feet, to accurately superimpose virtual wires 42 over the real world wiring board 14 within 0.2 inch of the desire location, and to operate in "near real time" by having an update rate of approximately 60 Hertz and a latency period of approximately 16 milliseconds.
25 The fiducial-based tracking system of the present invention is scaleable to accommodate larger or smaller volumes and a variety of volume forms. Therefore, the AR system can be modified to function within other volumes as required by a particular application.

Referring to Figures 7-8, the software 52 operating on the computer 16 may generate menu driven screen displays 72, or pull down menus, that form part of the user interface and
30 allow a user to easily navigate through large amounts of virtual information. The display 36 can be toggled between these menu driven screen displays 72 and other augmented views. A user 24 may move the cursor 74 through body movement. In the wire harness fabrication system illustrated in the figures, for example, the user 24 moves the cursor 74 by moving his or her head. As shown in Figure 8, the menu item is highlighted when the cursor is positioned over the

5 item. That menu item is selected through the user actuated selector device, which may take a number of forms including a manual toggle switch, a voice recognition system, or devices for detecting eye movement. For example, a user may speak a command or blink his or her eyes to select a menu command.

10 Manu commands for the wire harness fabrication AR system may include: OVERVIEW, SHOW ALL SYMBOLS, PREVIOUS WIRE, CURRENT WIRE, NEXT WIRE, STATUS, CLOSE MENU, and RESTART PROGRAM. The OVERVIEW command shows the entire design for the harness, including all of the wires. The SHOW ALL SYMBOLS command shows where to place the “clecos,” fixtures, or connectors. Clecos are removable pegs that fit within the pegboard. They allow a single pegboard to be easily modified for a wide variety of harness
15 designs; whereas the wiring board for the known art are fabricated for a specific wire harness design. The PREVIOUS WIRE command shows the wire that was worked on last. The CURRENT WIRE command shows the wire that is being worked on currently. The NEXT WIRE command shows the wire to be worked on next. The STATUS command shows the overall status of the harness build. The CLOSE MENU command makes the pop down menu
20 disappear. The RESTART PROGRAM command enables the user to choose another harness for assembly or to simply quit. These menu commands illustrate the ease of using the AR system to navigate through a complicated process and retrieve the appropriate information using the AR system.

The process of identifying and tracking the relative position between objects and the user
25 performed by the tracker must be efficient, accurate, and “intelligent” to allow the AR system to operate in near real time. Referring again to Figure 1, the tracker system includes the sensor(s) 26 for detecting the pattern of fiducials 12 disposed on the object surface 14, signal processing and power electronics 46, the processor 18, and further includes a video feature extractor (VFE) 48 and the tracker application software program 56 operating within the processor 18. The
30 tracker system identifies and tracks the relative position between the target object(s), such as the surface object 14, and the sensor(s) 26 by detecting fiducials and calculating the tracking parameters.

The signal generated by the sensor 26 is passed through the VFE 48. The VFE 48 receives and formats composite video signals from the sensor 26 or camera. Figure 2 is an

5 electrical schematic of the VFE 48. The VFE 48 enhances the efficiency of the tracking process, and contributes to the near real time capabilities of the AR system 10 by extracting the relevant information from the video signal through the bandwidth reduction circuit 84. The VFE 48 of the embodiment shown in the figures is a PCMLA card. The signal from the sensor 26 is received by an I/O connector 86 on the VFE 48, and the extracted data from the VFE 48 is
10 passed to the data bus of the computer 16 through the PCMCIA port 88. The bandwidth reduction circuit 84, for Feature Generator and Sync Separator, strips out the synchronization signals from the data signal, and detects the leading and trailing edges of fiducials. The VFE 48 reduces the bandwidth of the signal by accurately detecting the beginning and ending pixel of a fiducial during each video raster run. The line number, the beginning pixel number for a
15 fiducial, and the number of continuous pixels after the beginning pixel are extracted from the signal for each fiducial detected in the scan line. This extracted information is called a "run" and is passed to the processor by the VFE 48.

The VFE 48 filters and removes video noise or garbage from the signal. An "initial correspondence" process calculates the bounds of expected runs, which reflect the known
20 dimensions the individual fiducials and the estimated position of the sensor, beyond which no real fiducial would extend. The VFE 48 uses this bounds of expected runs to eliminate noise or garbage by rejecting runs that are either too large or too small to be a fiducial. Therefore, by filtering out noise and background, the VFE 48 efficiently reduces the amount of data processed by the computer to a manageable level. The data run is placed in a FIFO buffer 90 if it is not
25 rejected as garbage or noise. The processor 18 retrieves the data run information from the buffer 90 as needed.

Referring again to Figures 1 and 9-14, the pattern of fiducials 12 includes a geometrically consistent hard fiducial pattern 32 and a pseudo random soft fiducial pattern 34. The hard fiducial pattern 32 is shown as a evenly spaced or geometrically consistent, rectilinear shape.
30 However, the hard fiducial pattern 32 may be formed from other geometrically consistent polygons or shapes. The soft fiducial pattern 34 is formed from individual coordinate marks that have either a larger or smaller size than the coordinate marks formed in the hard fiducial pattern 32. In the wire harness fabrication AR system embodiment shown in the figures, each of the hard fiducials have a unique diameter of 0.6 inches, and the diameter of any of the soft fiducials

5 may vary from 0.1 inch to 1.2 inches. At least one soft fiducial 34 is positioned within each polygon of hard fiducials 32. The location of the soft fiducials 34 is in one of the $n \times n$ locations (for example, an 8 x 8 grid or 32 x 32 grid) within each polygon of hard fiducials 32 is determined by a pseudo random number generation process. The relative position of the soft fiducial 34 with respect to the polygon of hard fiducials uniquely identifies that polygon within
10 the hard fiducial pattern 32.

The color of the pattern of fiducials 12 for the visual AR system 10 is contrasted to the color of the object surface. In the wire harness fabrication AR system embodiment, for example, the preferred color is determined by the spectral response of the sensor 26 (typically a CCD video camera), the wiring board color background desired by the operators, the color of any real
15 wires or other objects in the field of view, and the light level and spectral content of the light at the wiring board 14. A black board or object surface 14 and white fiducials 12 provide sufficient contrast to enable the tracker to accurately identify the relative position and orientation between the wiring board 14 and the sensor 26. The pattern of fiducials 12 preferably comprises passive fiducials; *i.e.* the fiducials 12 do not send a signal nor do they embed position information.
20 Rather, the position and orientation information is derived from the relationship between the geometrically consistent pattern of hard fiducials 32 and the pseudo random pattern of soft fiducials 34 as detected by the optical sensor 26.

Figure 19 illustrates the geometry represented by the six tracking parameters. The tracking parameters include three linear position parameters (X-bar 92, Y-bar 94, and L 96), and
25 further include three angular orientation parameters (phi 98, theta 100, and psi 102). The X-bar 92 and Y-bar 94 parameters determine the position along the object surface 14 or wiring board, and L 96, phi 98, theta 100 and psi 102 determine the orientation of the sensor. Figure 21 illustrates a possible image of a pattern of fiducials captured by the camera for a given orientation as determined by L 96, phi 98, theta 100 and psi 102. The size and shape of the
30 fiducials are affected by the orientation of the sensor 26.

Figure 23 illustrates a method for tracking the position and orientation of an object that is performed by the tracker application software 56 in the computer 52. An initial startup routine 110 loads the real world alignment data, such as a sensor-eye offset and factory alignments, from a database file in the memory 20 of the computer 16, compensates for known aberrations of the

5 sensor 26, and sets a gain for the sensor 26. The processor 18 then performs a clumping routine, in which the processor 18 executes selected algorithms that “clump” the individual data runs together to form individual fiducial representations and then finds the centroid of those “clumps.” The processor 18 then performs the correspondence process or routine 114, in which the processor 18 identifies or acquires the position of the “hard” fiducials using their known
10 geometric relationship based on the reference pattern of fiducials stored in the memory 20 of the computer 16. In the embodiment shown in the figures, a polygon matching the known hard fiducial configuration is found by first matching three fiducials, then trying to match a fourth hard fiducial, and then searching for additional clumps in the data which correspond to adjacent polygons of hard fiducials. After recognizing the hard fiducial polygon(s) in the sensor field of
15 view, the tracker estimates the sensor orientation (ϕ 98, θ 100 and ψ 102) and distance L 96 from the object surface 14 through an acquire routine. The processor 18 then performs an election process or routine 116, in which the tracker then evaluates clumps of data which could represent individual soft fiducials in the object plane. The location of the soft fiducials within the detected polygon is stored and compared to the stored fiducial pattern data. Referring to
20 Figure 20, each hard fiducial polygon may be considered to have an imaginary grid. At least one soft fiducial will be centered on one of the intersections of the imaginary grid. The position of \bar{X} 92 and \bar{Y} 94 depends on the position of the soft fiducial(s) within the hard fiducial polygon. The algorithm evaluates these results and determines the \bar{X} 92 and \bar{Y} 94 parameters that determines the position of the sensor field of view on the object surface 14.

25 Figure 24 illustrates the method of acquiring hard or soft fiducial marks. First, the tracker determines whether the fiducials have been previously acquired. If the fiducials have been previously acquired, the tracker performs a quick acquire routine 120 in which it calculates the theoretical parameter values for the fiducials based on the previous position(s) of the fiducials. The sensor position is tracked with respect to the object surface by comparing and
30 corresponding / electing clumps recorded in successive video fields. The movement of the sensor with respect to the object surface is tracked, and the movement data is used by the algorithm to predict immediate future locations of the fiducials within the sensor field of view. If the fiducials have not been previously acquired, the tracker performs a cold acquire routine 122 in which it sets factors or standards for the fiducial search 130, matches the clumps against

5 the reference pattern or scene 132, and compares the results to determine if they fall within the standards for the fiducial search 134. If the results do not fall within the standards, the fiducial search and area factors are relaxed 136, and the tracker performs the matching 132 and comparing 134 processes again. After acquiring estimated values fore the tracking parameters, the tracker performs an iteration process 138 until the detected pattern of fiducials match the
10 reference pattern of fiducials to within a desired convergence. The iteration process is illustrated in Figure 22 where a correspondence process is occurring between a calculated or reference pattern of fiducials and the detected pattern of fiducials. The iteration process “fine tunes” the calculation of the tracking parameters to accurately determine the relative position and orientation between the sensor and the object surface.

15 The descriptions above and the accompanying drawings should be interpreted in the illustrative and not the limited sense. While the invention has been disclosed in connection with the preferred embodiment or embodiments thereof, it should be understood that there may be other embodiments which fall within the scope of the invention as defined by the following claims. Where a claim, if any, is expressed as a means or step for performing a specified
20 function it is intended that such claim be construed to cover the corresponding structure, material, or acts described in the specification and equivalents thereof, including both structural equivalents and equivalent structures.